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The results show that the Neuber notch analysis is not as good an indicator of the low cycle fatigue behavior of A723 steels as is the fracture mechanics life prediction technique. As the life cycles-to-failure decreases, the Neuber analysis predicts lives that are two to three times more conservative than those experimentally measured. Since the fracture mechanics approach and the elastic Neuber approach are fully elastic stress-based, one can conclude that for this class of steels, an elastic-based life predictions technique works even through we are believed to be in a plastically-dominated regime.

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TABLES

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NOMENCLATURE

a	-	crack length
b	-	fatigue strength exponent
c	-	fatigue ductility exponent
C	-	Paris equation fatigue coefficient (MPa$\sqrt{m}$)
Δe	-	remote applied strain range (mm/mm)
Δe_e	-	remote applied elastic strain range (mm/mm)
Δe_p	-	remote applied plastic strain range (mm/mm)
$\Delta \varepsilon$	-	local true strain range (mm/mm)
$\Delta \varepsilon_e$	-	true elastic strain range (mm/mm)
$\Delta \varepsilon_p$	-	true plastic strain range (mm/mm)
ε_f'	-	fatigue ductility coefficient
E	-	elastic modulus (GPa)
ΔK	-	stress intensity factor range (MPa$\sqrt{m}$)
K'	-	cyclic strength coefficient $(= \sigma_f'/(\varepsilon_f')^{n'})$
K_f	-	stress concentration factor
n	-	strain-hardening exponent
n'	-	cyclic strain-hardening exponent (= b/c)
$2N_f$	-	reversals-to-failure
R	-	strain ratio
ΔS	-	remote applied stress range (MPa)
$\Delta \sigma$	-	local true stress range (MPa)
σ_f'	-	fatigue strength coefficient (MPa)
σ_{YS}	-	material yield strength

INTRODUCTION

This study was undertaken in order to investigate the low cycle fatigue response of two types of A723 steel. Typical applications require that these steels possess safe fatigue lives in the 2000 to 3000 cycle regime. The study investigates fatigue cracks emanating from smooth notch-free surfaces, and from semi-circular notches with a stress concentration factor, $K_T = 1.4$, under four-point bending conditions. Specimen geometry, test fixture setup, and notch configuration are shown in Figure 1. Experimentally measured lives are then compared with those predicted by elastic and elastic/plastic Neuber notch analysis (refs 1.2) and the classical fracture mechanics life prediction approach.

Both steels, referred to as A723 and A723(Ni), were processed with the vacuum arc remelt (VAR) processes; the A723 was single VAR processed, and the A723(Ni) was triple processed. They are essentially the same in chemical makeup (Table 1), with two exceptions. The A723(Ni) was produced with higher nickel (~3.4 percent) and higher vanadium (~0.14 percent) than the A723 steel. The added nickel produces better low temperature toughness, and the added vanadium, better grain refinement.

Table 1. Chemical Composition
(Weight Percent)

Element	A723 Steel		A723(Ni) Steel	
	Min.	Max.	Min.	Max.
Carbon	0.31	0.36	0.31	0.35
Phosphorus		0.010		0.010
Sulfur		0.008		0.010
Silicon		0.25		0.30
Nickel	2.20	3.20	3.25	4.00
Chromium	0.90	1.30	1.10	1.30
Vanadium	0.04	0.12	0.12	0.15
Manganese	0.55	0.75	0.50	0.90
Molybdenum	0.30	0.65	0.40	0.60

As-measured mechanical properties for both steels are shown in Table 2. Note the higher strength of A723(Ni) with only minor decreases in reduction in area and elongation. Also note the low temperature Charpy impact energy is the same for the A723(Ni) as for the lower strength A723 steel.

Table 2. Mechanical Properties

Property	A723 Steel	A723(Ni) Steel
0.2% Yield Strength (MPa)	1068	1124
Ultimate Tensile Strength (MPa)	1172	1200
Reduction in Area (%)	54	50
Elongation (%)	15	13
Charpy Impact Energy (J, -40°)	57	57
Elastic Modulus (GPa)	205	205

THEORY

The approach utilized in this investigation was to develop a simple strain-deflection correlation. A smooth specimen was strain gaged at the maximum strain location (Figure 1), and strains were measured at deflections up to 15 millimeters. Results of testing can be seen in Figure 2. Testing was completed in a displacement controlled servo-hydraulic test system with the ratio of maximum-to-minimum displacement equal to -1.0 (R = -1.0). Observe that even at relatively large deflections, the measured strains measure remained essentially linear. This relationship was utilized in subsequent tests to determine outer fiber strains, based on machine-monitored load line deflection. Smooth and notched specimens of both steels were then loaded in the four-point bend fixture and tested until final failure. The theory and equations utilized for each predictive technique are described below.

NEUBER NOTCH ANALYSIS

Elastic Applied Remote Loading

The theory behind utilization of the Neuber notch analysis is that if the remote applied stresses and strains away from a notch (stress concentrator) are known, then the local stresses and strains in the notch can be approximated. The form of Neuber's equation is as follows:

$$K_f(\Delta S*\Delta e*E)^{1/2} = (\Delta\sigma*\Delta\varepsilon*E)^{1/2} \tag{1}$$

where ΔS and Δe are the remote applied stress and strain, $\Delta\sigma$ and $\Delta\varepsilon$ are the local stress and strain (in the notch), and E is the elastic modulus. For the case where the remote nominal applied loading is elastic, Neuber's equation takes the form

$$K_f(\Delta e * E) = (\Delta\sigma * \Delta\varepsilon * E)^{1/2} \qquad (2)$$

Once the product of the local stresses and strains in the notch is known, then the life of the notch can be calculated by a trial and error procedure via the ASTM fatigue equation

$$\Delta\varepsilon = 2\left[\frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c\right] \qquad (3)$$

and the cyclic stress/strain equation

$$\Delta\sigma = 2K'\left(\frac{\Delta\varepsilon_p}{2}\right)^{n'} \qquad (4)$$

where $\Delta\varepsilon_p$ is calculated by the Coffin-Manson equation

$$\Delta\varepsilon_p = 2\varepsilon_f'(2N_f)^c \qquad (5)$$

Plastic Applied Remote Loading

For the case of remote plastic applied loading, Eq. (1) no longer simplifies to Eq. (2). Hence, another relationship between ΔS and Δe is necessary. For this we utilize the elastic-plastic stress strain relationship given as

$$\Delta e = 2\left[\frac{\Delta S}{2E} + \left(\frac{\Delta S}{2K'}\right)^{\frac{1}{n'}}\right] \qquad (6)$$

Then by a trial and error procedure, utilizing Eqs. (3), (4), and (5), the lives are calculated in the same manner as the fully elastic case.

Determination of Fatigue Constants

In order to effectively approximate the fatigue life of a given notch with Neuber analysis, the fatigue constants b, c, ε_f', σ_f' must be established. Critical fatigue constants are published in the open literature (ref 3), however, none were found for A723 steels. The fatigue constants are determined by evaluating the fatigue life of the unnotched smooth specimens in the four-point bend fixture shown in Figure 1. At a point during the life cycling (approximately 50 percent $2N_f$), a stress strain hysteresis loop was taken, and values of Δe_e and Δe_p were

measured. Plots of the elastic, plastic, and total strain ranges versus reversals-to-failure for A723 and A723(Ni) are tabulated in Tables 3 and 4, and shown in Figures 3a and 3b, respectively. These plots are superimposed on each other in Figure 3c. Since the measured strains and lives were similar for both alloys, a single calculation of the constants was made for both alloys.

Table. 3. Fatigue Results, Unnotched A723 Steel

$2N_f$	Δe (mm/mm)	Δe_e (mm/mm)	Δe_p (mm/mm)
11170	0.00873	0.00825	0.00048
6580	0.01021	0.00858	0.00163
3650	0.01058	0.00897	0.00161
3370	0.01199	0.00903	0.00296
3100	0.01324	0.00908	0.00416
1650	0.01465	0.00951	0.00514
1230	0.01850	0.00952	0.00898
629	0.02013	0.01023	0.00990
270	0.02723	0.01091	0.01623
104	0.03522	0.01172	0.02350

Table 4. **Fatigue Results, Unnotched A723(Ni) Steel**

$2N_f$	Δe (mm/mm)	Δe_e (mm/mm)	Δe_p (mm/mm)
14590	0.00873	0.00809	0.00064
5560	0.01280	0.00869	0.00411
1040	0.01850	0.00986	0.00864
940	0.01761	0.00993	0.00768
109	0.03744	0.01167	0.02577
102	0.03744	0.01173	0.02571
93	0.04166	0.01181	0.02985
82	0.04166	0.01193	0.02973

Calculations of ε_f' and c are made with the Coffin-Manson equation (Eq. 5), and σ_f' and b are evaluated with the Basquin equation

$$\Delta\varepsilon_e = 2\frac{\sigma_f'}{E}(2N_f)^b \tag{7}$$

The calculated fatigue constants for A723 steels are shown in Table 5. Also shown in the table are fatigue constants as published in Reference 3 for quenched and tempered 4340 steel, which has a similar chemical composition, but a significantly higher yield strength (σ_{YS} = 1241 MPa).

Table 5. Fatigue Constants for A723 and 4340 Steels

Steel	ε_f'	σ_f' (MPa)	b	c	n′	K′ (MPa)
A723	0.146	1717	-0.075	-0.52	0.14	2248
4340	0.730	1655	-0.076	-0.62	0.14	--

Note the good agreement of the published fatigue properties σ_f', b, and c of 4340 steel and those measured for A723 steel. The ε_f', however, varies considerably for the two steels. The difference between the monotonic and cyclic strength of A723 is over 600 MPa, while for 4340 it is approximately 400 MPa. The A723 steel experiences a more severe cyclic strengthening mechanism, which manifests in a drastically lower fatigue ductility than 4340 steel.

Fracture Mechanics Approach

This approach utilizes the well-known Paris equation (ref 4)

$$\frac{da}{dN} = C\Delta K^{n} \tag{8}$$

to predict the life of the notched component. Previous work by Underwood and Throop (ref 5) has determined that for the A723 steels, the following constants apply: $C = 6.52 \times 10^{-10}$ m/cycle and $n \approx 3$. The ΔK expression utilized was $\Delta K = 1.12\, \Delta\sigma \sqrt{\pi a}$ where $\Delta\sigma = K_f\, E\, \Delta e$ and $K_f = 1.4$.

Once integrated, the Paris equation takes the form of

$$2N_f = \frac{1.611x10^{-6}}{\Delta e^3}\left(a_i^{-1/2} - a_f^{-1/2}\right) \tag{9}$$

Inspection of the solution of the Paris equation reveals that the results obtained are highly dependent on the initial flaw size, a_i. This fracture mechanics prediction technique assumes an a_i of 4.0 μm, which is typical for a milled surface (ref 6) like the one used in this analysis.

TEST RESULTS

The experimental results of testing A723 steels under four-point bending conditions with notches (K_f = 1.4) are tabulated in Table 6.

Table 6. Fatigue Results, Notched A723 Steels
$K_f = 1.4$

$2N_f$	Δe (mm/mm)
4520	0.00540
1300	0.00873
1070	0.00873
610	0.01021
240	0.01324
194	0.01324
126	0.01465
95	0.01850

The strains reported are the maximum outer fiber stains. These results are plotted in Figure 4, along with the corresponding smooth specimen fatigue results, which are also plotted against peak outer fiber strains. As expected, a significant decrease is observed in the measured lives.

Figure 5 shows the experimental results of testing plotted with the Neuber life prediction (elastic and elastic/plastic), and the fracture mechanics life predictions. Observe that the elastic/plastic applied loading Neuber prediction is approximately one-third of the measured life in the extreme low cycle fatigue regime. However, as the life cycles-to-failure increases, the elastic/plastic Neuber analysis predicts lives that are nearly exact. The elastic Neuber prediction fits the measured data well in the low cycle regime, although it tends to overpredict at longer lives-to-failure. The fracture mechanics approach predicts lives that are nearly exactly the same as those measured over the entire range of lives investigated.

SUMMARY

1. This analysis has shown that smooth bar fatigue data can effectively be utilized to predict notched geometry fatigue lives.

2. The elastic-based life predicting technique results closely approximate the experimental results. Under high strain loading conditions, the fatigue response of A723 steel is predominantly elastic dominated. This conclusion is validated by the fact that the fracture mechanics predictions, which are elastic-based, and the elastic remote loading-based Neuber analysis are a much better predictor of fatigue lives in the low cycle fatigue regime than the elastic/plastic remote loading Neuber analysis.

3. An elastic-based stress analysis, in conjunction with a fracture mechanics fatigue life approach, or elastic-based remote loading Neuber prediction will suffice when approximating the fatigue life of notched A723 steels. Special care should always be taken in measuring the initial a_i when utilizing the fracture mechanics approach. Results of testing can vary drastically if an incorrect a_i is utilized.

4. The fact that ε_f' is so much lower for A723 steels than for 4340 steel suggests that the plastic portion of the overall strain plays a less dominate role in fatigue, especially low cycle fatigue, than was previously thought. The discrepancy in measured ε_f' between that measured in this study and that published in the open literature results in a drastically different outcome. The fact that the cyclic strength of A723 is significantly higher than the static monotonic strength verifies that the A723 goes through a rather severe strengthening mechanism. This large increase in strength is not seen in the 4340 steel. The increase in strength is the likely cause for the relatively low fracture ductility of A723 with respect to 4340.

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6. "American National Standard on Surface Texture," ANSI B46.1-1978, The American Society of Mechanical Engineers, New York, NY, 1978, p. 16.

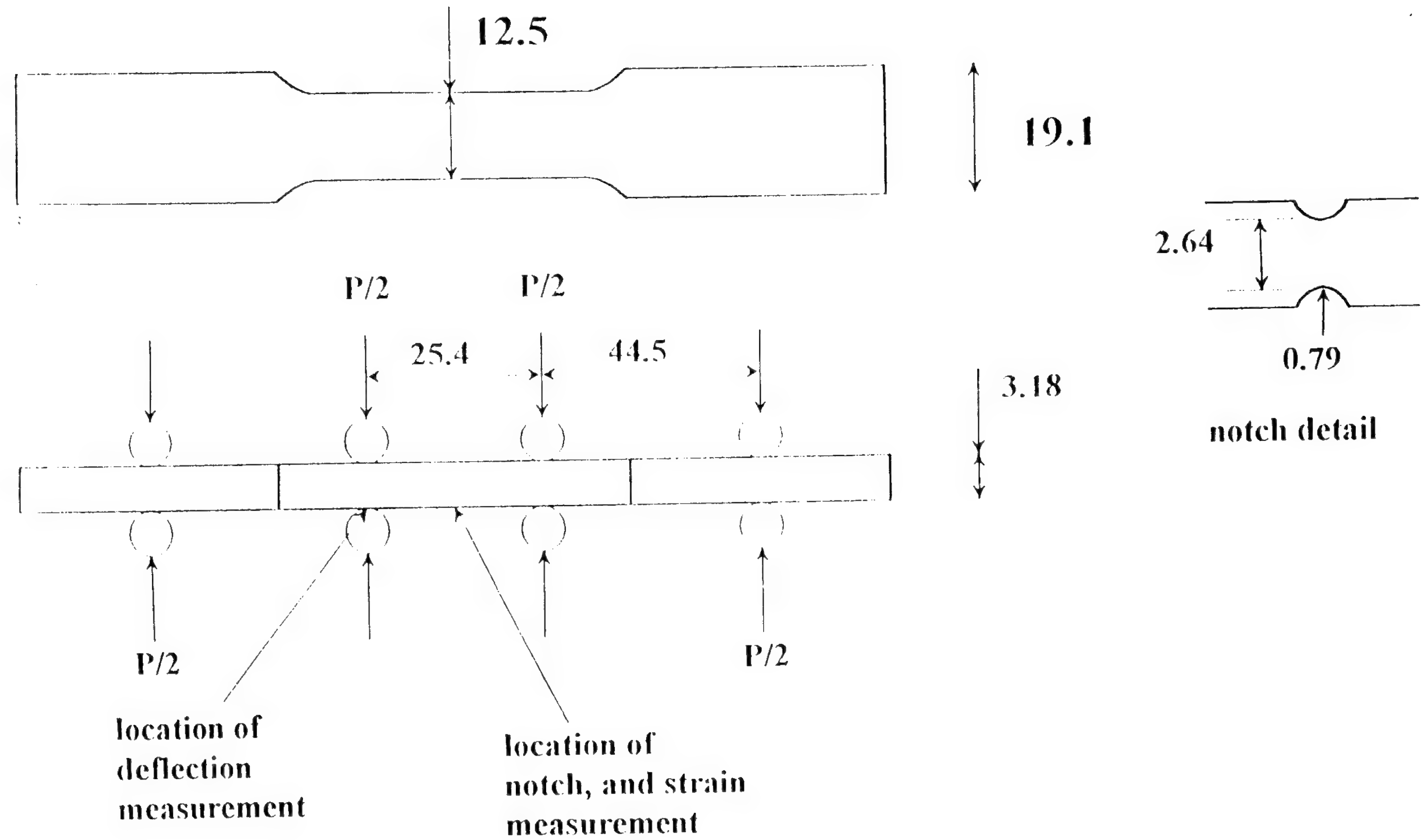

Figure 1 - Schematic of test fixture and specimen geometry, all dimensions in millimeters.

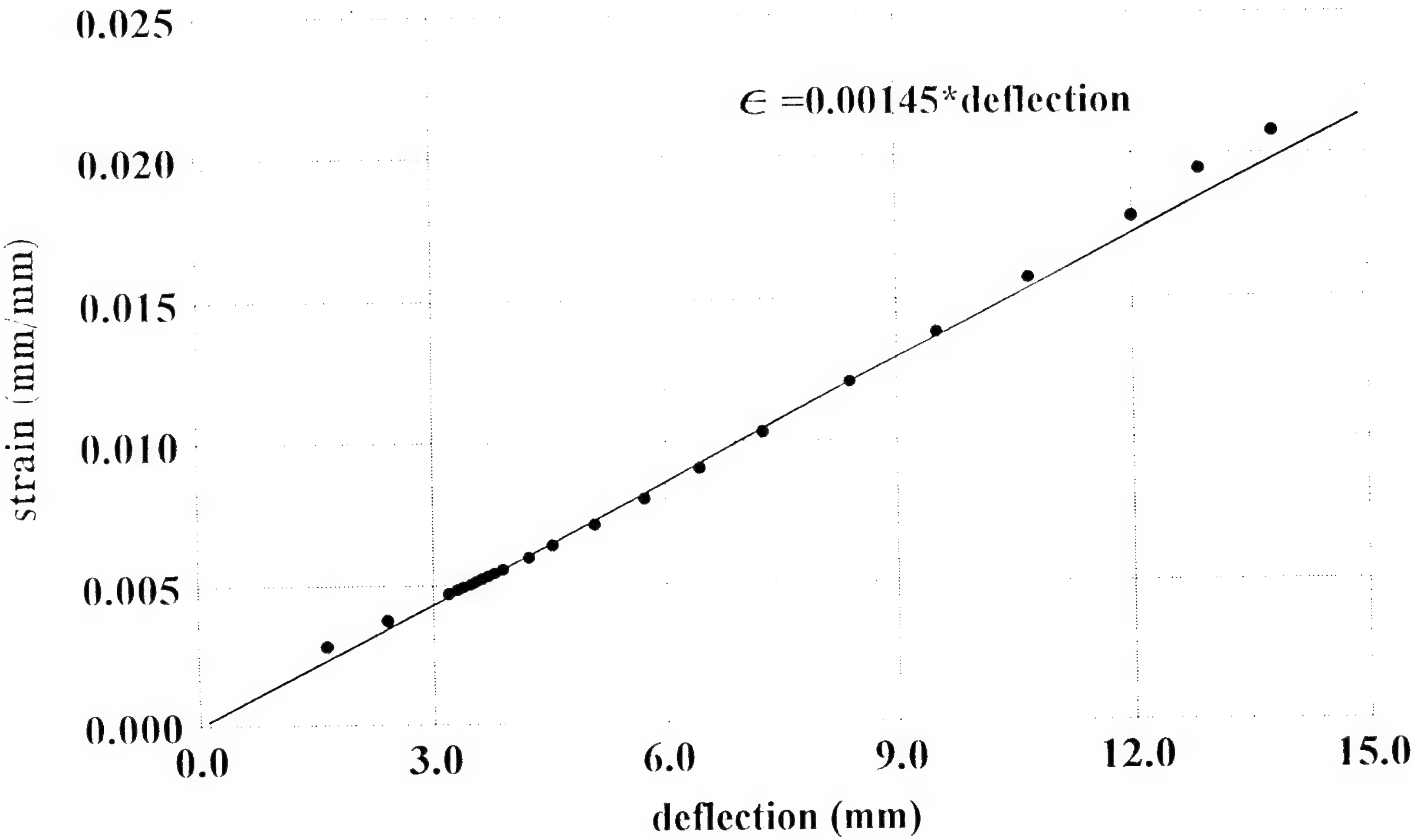

Figure 2 - Outer fiber strain vs. deflection for test setup and geometry shown in Figure 1 for A723 steel.

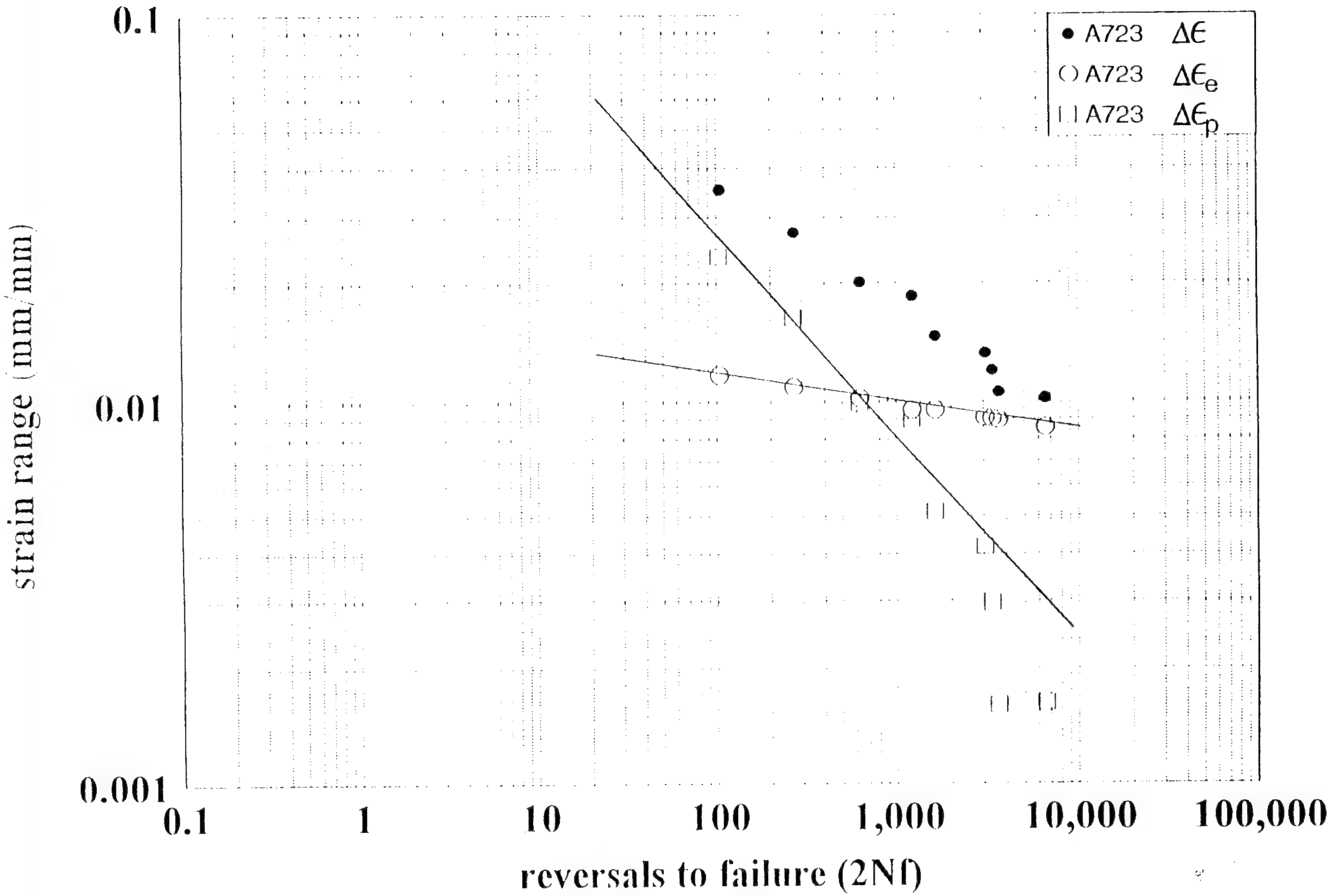

Figure 3a - Determination of fatigue constants, A723 steel

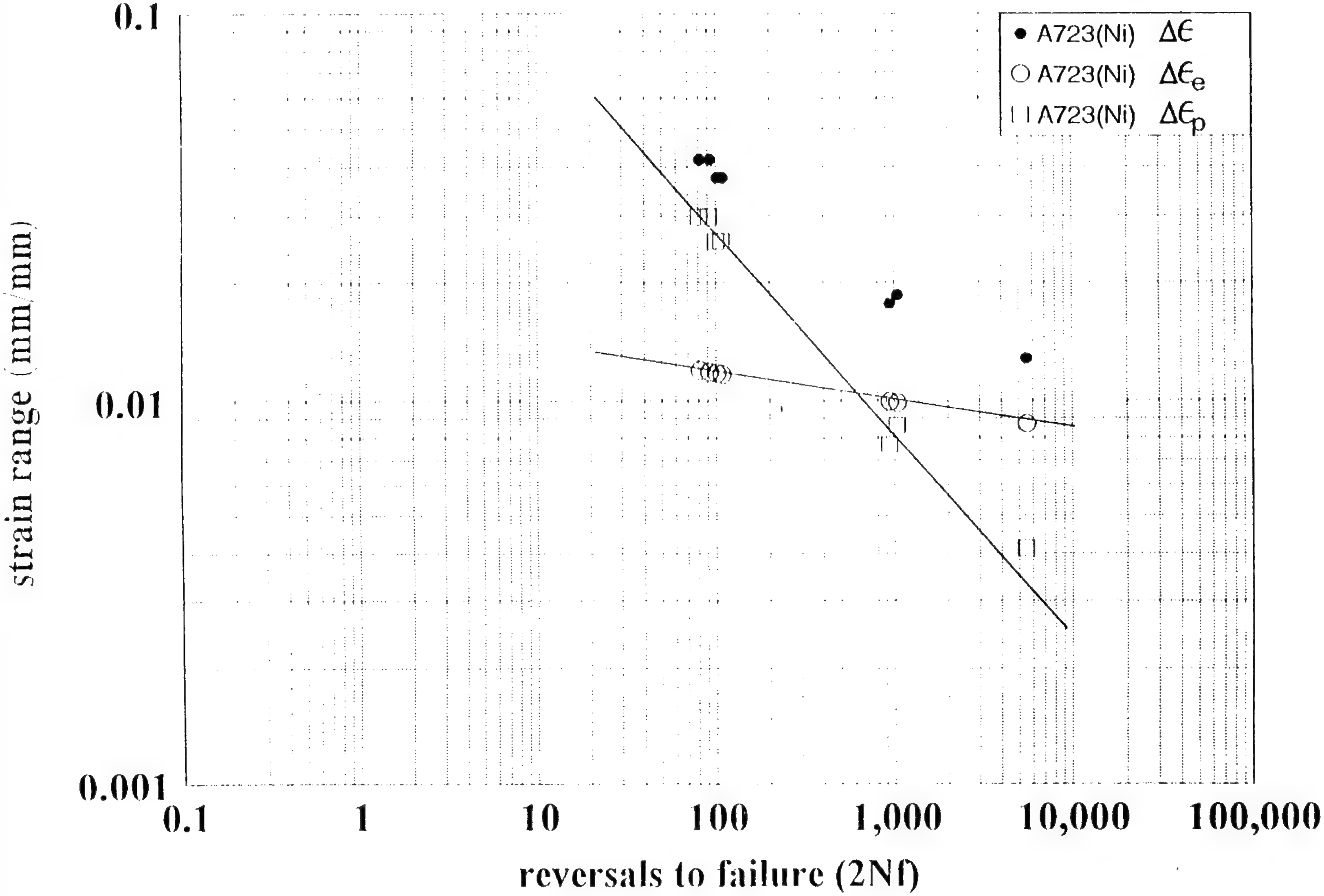

Figure 3b - Determination of fatigue constants, A723(Ni) steel

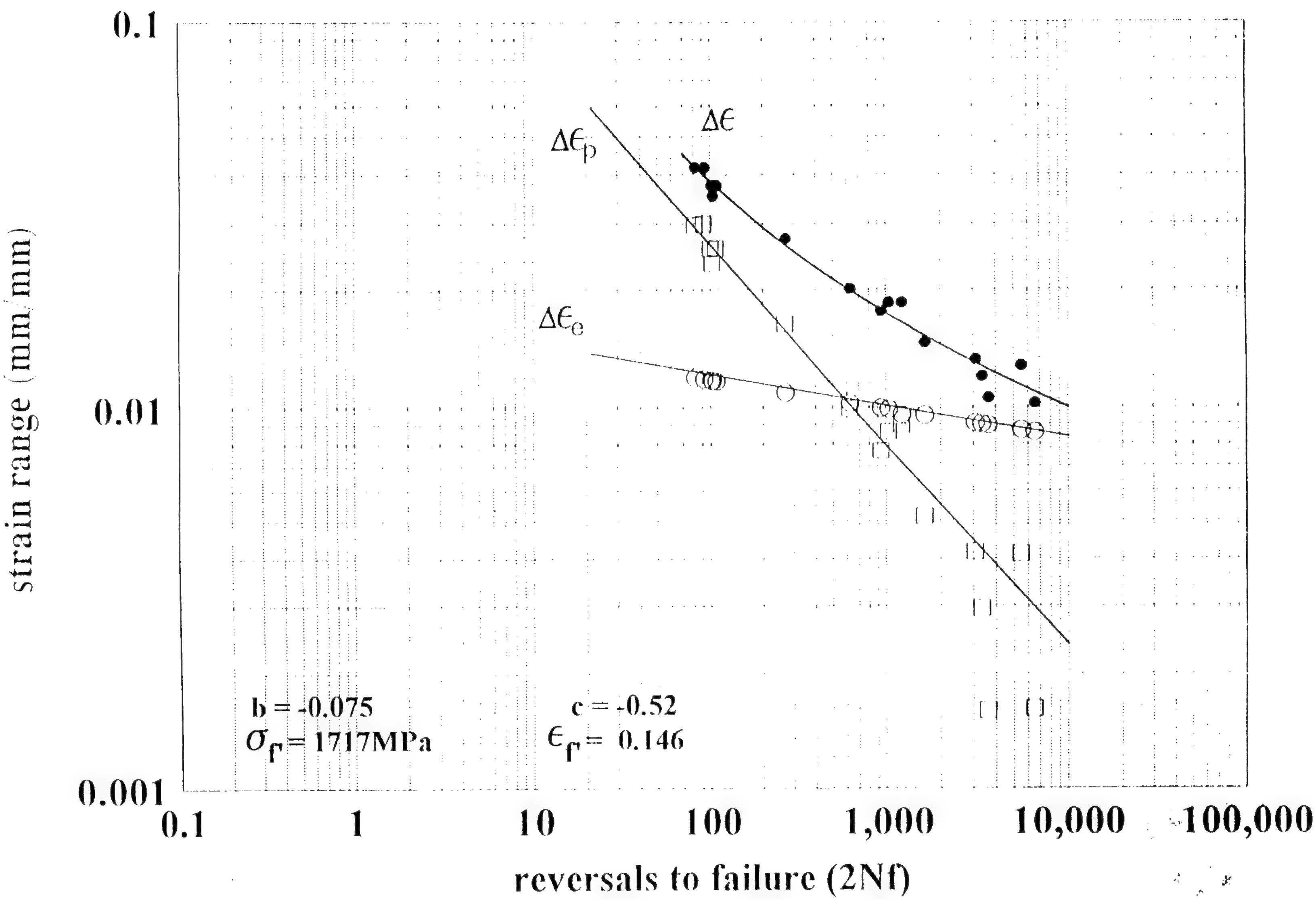

Figure 3c - Determination of fatigue constants, A723 and A723(Ni) steel

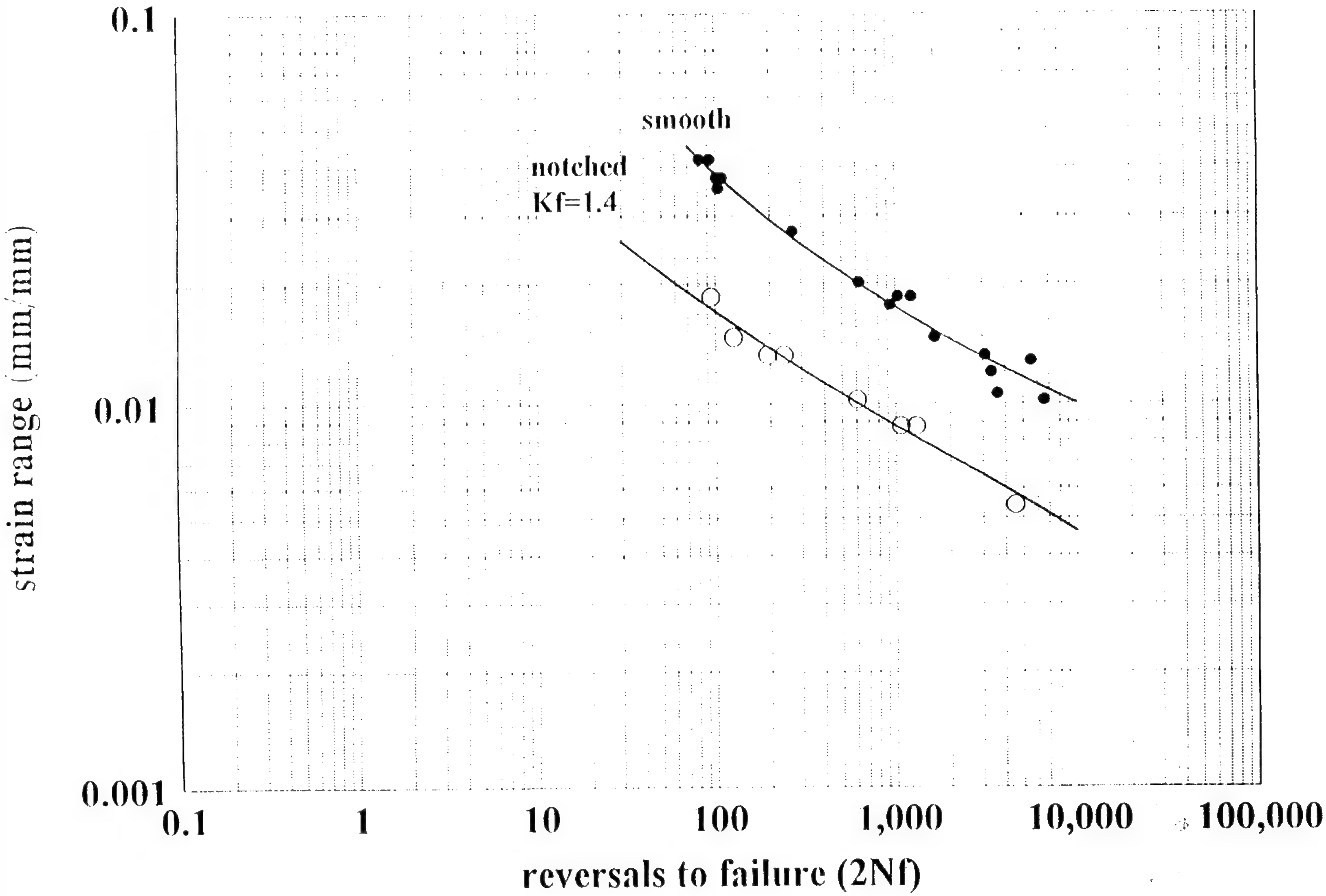

Figure 4 - Fatigue test results, smooth and notched, A723 and A723(Ni) steel

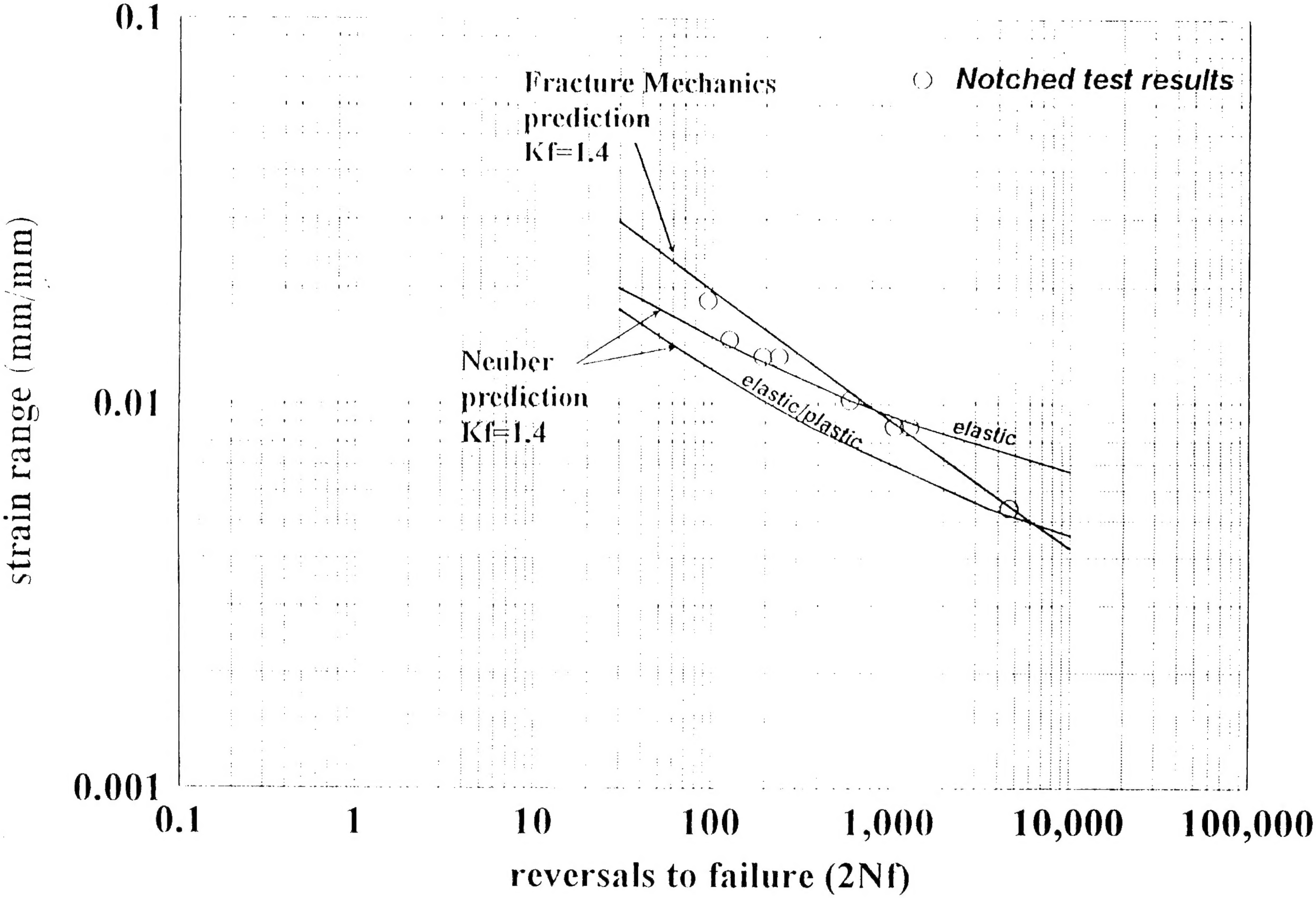

Figure 5 - Predicted and measured notched fatigue results, A723 and A723(Ni) steel

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